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ARCING FAULT PROTECTION IN LV AND MV POWER INSTALLATIONS

Abstract: As the result of long year investigations in the field of electric fault arc processes and protection, the paper presents a protection concept based on the electric arc energy to be expected in case of arcing, covering the special needs of protection in the switchgear assembly or cable system under consideration.

First an overview is given on the main reasons and sources of arcing. Then the consequences of fault arcs are considered. A special consequence of arcing faults in the LV range is the current-limiting effect. A method of the calculation of the arcing fault currents is presented for solving protection problems by guaranteeing fault switching-off and selectivity of the conventional network or line short-circuit protection. Special ultra-fast acting arc detecting and extinguishing devices are presented for complementing the conventional network short-circuit protection and personal protection in according cases.

1. INTRODUCTION

In spite of a high manufacturing quality and type-testing of switchgear assemblies and other electric power installations, and permanently improved construction and design, faults and malfunctions cannot totally be excluded. External effects and impacts, material defects, incorrect or insufficient maintenance and human errors may cause internal faults resulting in arcing between the active phases or line-to-ground. Own studies show the physically conditions of forming stable arcs to be generally given in low-voltage switchgear with short-circuit currents of more than 1,000 A [1]. In general the development to a three-phase arcing fault is typically.

Almost all short-circuit s in electric power systems and installations are accompanied by internal arcing and electric fault arcs. Arcing fault protection is an essential part of the short-circuit protection, but must often go beyond the short-circuit protection of the network or power system. Arcing fault protection must minimise the risk of personal injury, must reduce destruction and damages of installations and equipment and must prevent supply interruptions and outages of production. Often the costs of subsequent damages are still higher than those resulting from the direct arc effects. As shown by statistics on accidents and faults, high risks for arcing do especially exist in the low-voltage range (rated system voltages up to 1 kV).

Arcing fault protection is one of the most important aspects in constructing, planning, building and operation of electric power installations and systems. But it has some specialities compared to other aspects of the construction and dimensioning of electric equipment.

Arcing fault protection is often managed by single measures or general solutions which are not adapted to the specific demands of the related case. Until now there are no concepts or solutions of differentiated or distinguished means.

In cases of an arcing fault electric high-current arcs are formed, migrating within the installations in dependence on the fault duration and the special electric and geometrical conditions.

The main causes of internal arcing faults are shown in Fig. 1, resulting from a long-year analysis of low-voltage power supply in industry and power stations as well as in the utility field.

Causing extreme high power densities, the fault arcs are of high damaging risk for personnel injury and equipment. Amongst the dynamic and thermal effects of the fault current, there are direct arc impacts as

- the fast heating-up and nearly explosion-like extension of the arc discharging channel and the directly surrounding air causing a fast and high pressure increase within the inner switchgear (0.2...0.3 MPa)
- the high material-destroying temperature (5...20 * 10^3 K) of the stationary arc.

Fig. 2 presents an overview on the potential direct and indirect arc consequences.

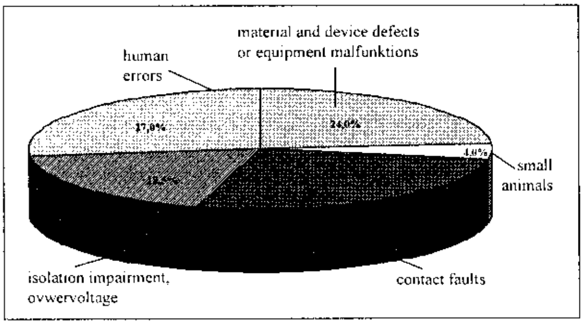

Fig. 1. Causes of arcing faults

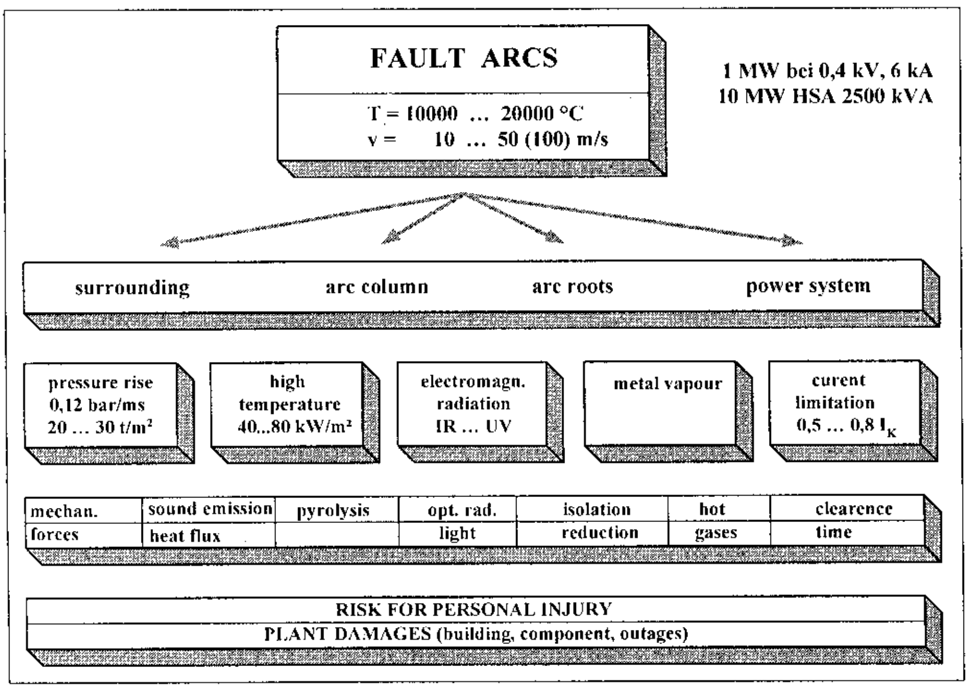

Fig. 2. Effects of arcing faults

2. CHARACTERISTICS OF ARCING FAULTS AND CONSEQUENCES

As mentioned the electric arcs are very intensive heat sources. In the limited volume of an installation (e.g. a switchgear compartment) the surrounding air is heated up explosion-like. With a resulting pressure rise of 0.02 to 0.03 MPa per ms the inner pressure reaches the maximum values of 0.2 to 0.3 MP within 5 to 15 ms (compression period). This means a pressure of about 20 to 30 tons per square meter. Besides of the direct dynamic or mechanical destruction, risks for persons especially result from this due to catapulting-away parts of the plant (doors, parts of enclosures or cabinets, panels, covers etc.). Under circumstances there is the risk of damaging the building. The pressure wave may also have a force on the human body [2].

The pressure extension is accompanied by an intensive sound emission (explosion bang). The sound pressure levels may exceed 140 dB and, thus, lead to health damages of the human ears.

Also nearly non-delayed, electromagnetic radiation in the whole relevant wave length range from UV to IR is emitted (continuous spectrum). The intensive light emission (well-known from welding) is very dangerous. A reduced risk does exist only in case of a closed plant.

In the expansion period (until about 20 ms after fault ignition) hot gases (plasma, metal vapour) begin to stream-out in direction to the pressure dissipation. After that, in the emission period lasting until about 150 ms after fault ignition, there is a pressure rise in the building or room which may damage or, in case of adverse constructive or volume conditions, just destroy the buildings. In the M.V. range often those damages were caused.

In the following thermal period of an arcing fault there are effects due to the intensive heat radiation, conduction and convection. The energy density of the heat flux is very high. In a distance of 30 cm to the arc (according to the working position of persons), e.g. an energy density of more than 500 kJ/m^2 may appear with short-circuit currents of about 10 kA. Ignition and pyrolysis of materials in the closer and also in the wider surrounding (up to 3 m) may happen. There is a high risk of fire; about 7 % of all electric arcing fault conduct in fire.

In addition, risk for personal injury results from toxic decomposition products appearing due to the heat effects to insulation and other materials. In this connection the development of smoke and fumes in case of fire may not be underestimated and is assessed to be very dangerous.

As the result of the material melting at the arc roots at the electrodes, metal is vaporised. Above the evaporation heat of the electrode material there is a huge mass expansion. In case of copper (evaporation heat is 2300 °C) there is a factor of 67,000 for this mass expansion.

The hot metal vapour of the arc then cools-down again relatively fast. As long it is hot the vapour reacts with the air oxygen, resulting in metal oxides. These oxides also cooling down, they return from the gas to the solid state. In the air these particles become visible as black smoke (copper) or silver-grey one (aluminium). They are still very hot and cling to each surface touched: they melt-in. The surface conductivity of insulation respectively the reduction of isolating properties inside the installations after an arcing fault results from this, with carbon and soot being mostly less involved.

The arcing faults are stochastic processes. Migrations of the arc roots, arc length variations, extinguishing and new-firing of the arcs characterise that stochastic time-variant behaviour.

Particular characteristics of arcing faults are that

- the short-circuit includes 2 or more phases of the three-phase system
- the phase involvement can change during the arc occurrence and existence or between them
- the fault is not locally limited to the first fault point.

As the result, also the arc effects and consequences are stochastical and statistically distributed. Exposure indices and arc parameters are distributed in scattering ranges and have to be statistically analysed. Arc effects are especially dependent on the arc energy, often there is a proportionality between the arc energy and the effects [3].

3. THE ARC CURRENT-LIMITING EFFECT

An essential consequence of the electric fault arcs is, particularly in the LV range, the current limiting effect. The arcs at the fault point are non-linear and non-stationary electric impedances (resistances) in the fault current path. Acting additionally to the impedance of the short-circuit path, which are taken into account when calculating the prospective short-circuit current $I''_{k(3)}$, the arc resistance has a considerably decreasing effect to the short-circuit current [1]. As shown by fault analyses, the short-circuit currents $I''_{k(3)}$ (normally calculated) can be limited to about 30...60 % in practical cases in L.V. systems. This has to be taken into consideration in setting the protective devices. If the protection devices are set on the base of the "metallic" short-circuit currents (without considering arcs), an extended arc duration, a non-selective fault interruption, or even a protection level underflow would be possible in the event of arcing faults.

But the arc resistances are only hard to describe. Fault arcs are thermodynamic systems of non-linear and time-variable electrical behaviour depending upon a great number of different - also non-electrical - influences. Their resistance is, among others, determined by the electric circuit parameters and the electrode configurations, however stochastically changing. In principle, there is a current decreasing which can be characterised by a current limitation factor

$$k_B = I_{karc}/I''_{k(3)} = f(U_{rN}, R/X, d)$$

depending on the network rated voltage U_{rN}, the resistance-to-reactance ratio of the short-circuit path R/X and the electrode spacing d [1]. The real fault current I_{karc} is determined by the arc voltage U_B. This arc voltage is a function of the electric and geometrical parameters mentioned before. From extensive experimental studies in the high-power test lab the following empirical equations and parameters for the arc voltage were found.
For MV systems is:

coplanar bars: $U_B = 314\ \text{V} + 1{,}2\,\frac{\text{V}}{\text{mm}} \cdot d$ s = 0,47 (gamma distribution)

triangular bars: $U_B = 402\ \text{V} + 1{,}2\,\frac{\text{V}}{\text{mm}} \cdot d$ s = 0,42 (gamma distribution)

with s = standard deviation.
For LV systems is:

$d <= 60$ mm : $U_B = A + B \cdot (U_{rN})^x \cdot d$

$d > 60$ mm : $U_B = C \cdot (U_{rN})^y + D \cdot d$

d is the spacing between the arc electrodes respectively the bus bars for switchgear assemblies and distribution plant. The voltages have to be inserted in V.
The parameters of the arc voltages for LV systems different statistical probabilities are:

cumulative probability	A	B	x	C	D	y
minimum (for all d)	28,6	0,13	0,363	-	-	-
30%	43,0	0,22	0,77	0,27	1,08	0,98
50%	55,3	0,0115	0,91	0,81	0,94	0,88
80%	80,0	0,027	0,84	3,52	0,50	0,74
95%	140,2	0,019	0,98	5,06	0,40	0,78

For LV cable systems generally a current limitation factor of $k_B = 0.6$ can be assumed.

4. CALCULATION OF THE ELECTRIC PARAMETERS

Based on the evaluation of a great number of arcing fault measurements carried out at various switchgear constructions with different electric parameters of the fault circuit, a statistical mathematical model of fault arcs was developed. The arcs are described by the arc voltages. The calculations are done by solving the state differential equation system which characterises the network with arcing fault. By means of this model, using empirical input data for the arc voltages, a numeric calculation of arcing fault processes is possible. The time curves of currents and voltages in case of arcing faults are calculated by an according PC program. The kind of arc initiation (line-to-ground, line-to-line or 3-phase arcing with different electric firing angles of the single arcs) can be selected. Furthermore, preferable standard values for these parameters are internally provided if wished.

In the Fig.3 and Fig.4 the arc voltages as used in the calculation, and the fault currents representing the calculation results, are shown for an example. With the program the current decreasing can be determined by the current limiting factor k_B .

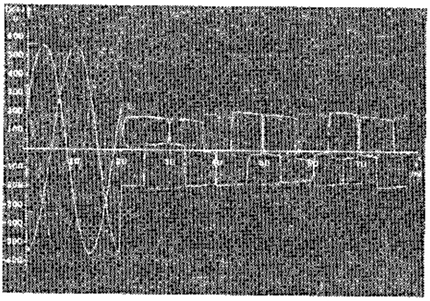

Fig 3: Arc voltages for a 3-phase arcing fault

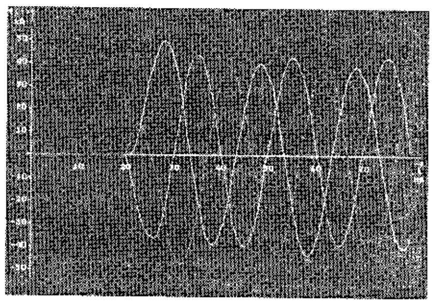

Fig 4: Arcing fault currents calculated

As the result the time behaviours of the arc power instantaneous values, the active arc power (Fig.5), and arc energy (Fig.6) are also available. There is a good accuracy of the calculation results as shown by comparisons with measurement results.

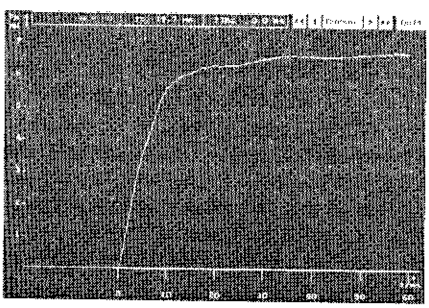

Fig.5: Total active power converted during arcing fault (calculated for an example)

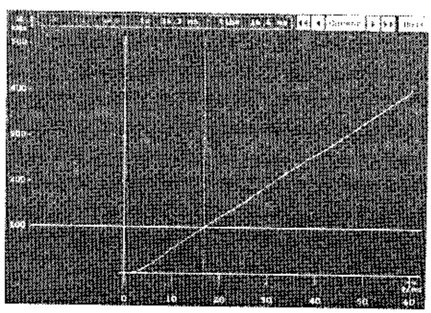

Fig.6: Arc energy converted (calculated for an example)

With knowing the energy and active power converted during arcing faults, permissible switchgear stresses can be verified.

5. PRINCIPLES OF ARCING FAULT PROTECTION

The first aim of the necessary arc protection is to prevent the arc occurrence by according design and construction of switchgear. But fault arcs cannot be prevented or excluded totally. There is always a remaining risk of arc occurrence. Thus measures of an active and preventive protection such as

- total or partial isolations, partitions
- separating compartments
- supervision, checking, and diagnostic of equipment during operation
- retrofitting of devices

have to be directed to reduce the probability of arc occurrence.

In a addition there must be additional efforts to limit the arc effects and consequences. We have practically to distinguish between a local limitation and a timely limitation of the arc. The physically relevant parameter is the arc energy having to be limited. The main way for this is to limit or reduce the arc existence duration (short-circuit time).

Otherwise, besides the timely limitation, in practice, the principle of local limitation is used. It means to limit arcs and their effects to the places of occurrence or a closed region of the construction so that no dangerous effects result outside. In practice arc resistance of switchgear and the prevention of impermissible outside arc effects is proved by means of type-testing. The test conditions are fixed as the result of the agreement of manufacturers/providers and customers operating the switchgear assemblies. That degree of protection only refers to a personnel one for closed switchgear and fire protection. The result of preventing danger outside of the switchgear construction has no relation to the destruction of switchgear or components inside. It does not mean switchgear protection.

In this connection, the categories switchgear or equipment protection and equipment functional protection were introduced. Personnel protection means the limitation of arc impacts to the inner switchgear. On the other hand, equipment protection means to limit the destruction of the equipment inside. Switchgear or equipment functional protection, respectively, is the highest degree meaning an arc effect reduction without functional impairment and irreversible destruction.

The arc effects are limited to such a degree that switchgear may be re-operated after a short period of fault clearance and cleaning (re-establishment of isolation etc.).

In special-directed test series, in particular, the relation between arc energy and equipment destruction were studied by changing the short-circuit capacity as well as the arc duration at a type-tested assembly of two circuit-breaker cubicles equipped as generally used (with cubicle partitions and compartments) [3].

There is a defined dependence of the damage extent in closed switchboards on the arc energy and migration. Arc energies below 100 kWs do not cause impacts requiring the exchange of equipment or components. Referring to an all-around and efficient switchgear and equipment protection, requiring to avoid irreversible destruction and supply interruptions to be as short as possible, an arc energy level of 100 kWs has to be guaranteed (switchgear functional protection).

In a range of about 250 kWs actually relative strong equipment damages occur. There is a heavy and dense smoke and combustion development. But the impacts are limited to the inner switchboards; the cubicles remain closed; pressure effects are safely controlled. Concluding it may be stated that personnel protection does exist in case of closed switchgear when the arc energy is limited to 250 kWs [4].

The PC program also allows to determine the arc energy to be expected in a special application. Following the conclusions can be drawn on what degree of personnel and equipment endangering can be achieved in dependence on the protective and switching devices available or have to be used. Advice for improving the arc protection level can be derived [5].

Starting from the permissible energy values of W_{LBper} = 250 kWs for personnel protection, W_{LBper} = 100 kWs for equipment functional protection, an allowed short-circuit duration t_{kper} can be determined:

$$t_{kper} = W_{Lbper} / P_{LB} .$$

Characteristic arc power values of real L.V. switchgear assemblies range between

$$P_{LB} = (0.22 \ldots 0.27) * S''_k .$$

S''_k is the short circuit capacity at the network coupling point of the switchgear

$S''_k = \sqrt{3}\ U_{rN}\ I''_{k(3)}$.

6. FAST ACTING ARC PROTECTION SYSTEM

These times often cannot be provided by the normal short circuit protection of the networks [4,5], a secondary protection is necessary, meaning additionally separate protective devices consisting of arc sensors and arc extinguishing devices. A special solution was developed. Solving inadequacies of other existing systems, the protection system developed is based of one or two different sensor systems and an arc quenching device. These components may be combined in different ways, depending of the actual protection needs. If necessary, total arc existing times below 5 ms may be guaranteed, independently upon other conditions. Thus, complete protection, personnel and equipment functional protection, may be provided in each practical case. Fig. 7 shows the principle scheme of the variable system. It can be used as switchgear component fixed mounted in the system as well as a transportable unit connected to the electric system in case of working activities, providing personnel protection also in case of opened installations (also e.g. for live working).

There are two sensor systems acting on the base on non-current-depending criteria (no direct current dependency). These detectors can be used in combination or also separately. By only use of one sensor type, two or more similar sensor systems can be applied for increasing the reliability of the protection system [6,7].

Fig. 8 shows an oscillogramme of an arcing fault extinguished by the protection system in the high-power test lab. The test was for a LV system with 420V test voltage and a prospective short-circuit current of 65 kA. The electric arc power would be 13.3 MW in case of unlimited arc. The arc duration is limited to 1.85 ms meaning a reduction of the arc energy to 6.8 kJ.

7. SUMMARY

Arcing fault protection is often managed by single measures or general solutions which are not adapted to the specific demands of the related case. Until now there are no concepts or solutions of differentiated or distinguished means. As the result of long year investigations in the field of electric fault arc processes and protection, the paper presents a protection concept based on the electric arc energy to be expected in case of arcing, covering the special needs of protection in the switchgear assembly or cable system under consideration. The studies of the arcing fault processes and ways of influencing the arc behaviour and consequences were based on theoretical investigations as well as the extended experimental ones and on-site measurements in the high power test lab. The paper summarises important result and experiences of these investigations.

A special consequence of arcing faults in the LV range is the current-limiting effect. The fault point impedances of the arcs reduce the short-circuit current significantly and result in serious problems with the time-dependent over-current protection devices. A method of the calculation of the arcing fault currents is presented for solving such problems by guaranteeing fault switching-off and selectivity of the conventional network or line short-circuit protection.

Special ultra-fast acting arc detecting and extinguishing devices are presented for complementing the conventional network short-circuit protection and personal protection in according cases. The guarantee the arc extinction in a time interval of less the 5 ms, meaning that installation as well as personal protection is provided in each fault case possible. The investigation results show that personal protection can be guaranteed also in case of direct arc exposure that is given for instance in case of live working or working near to live parts [8,9].

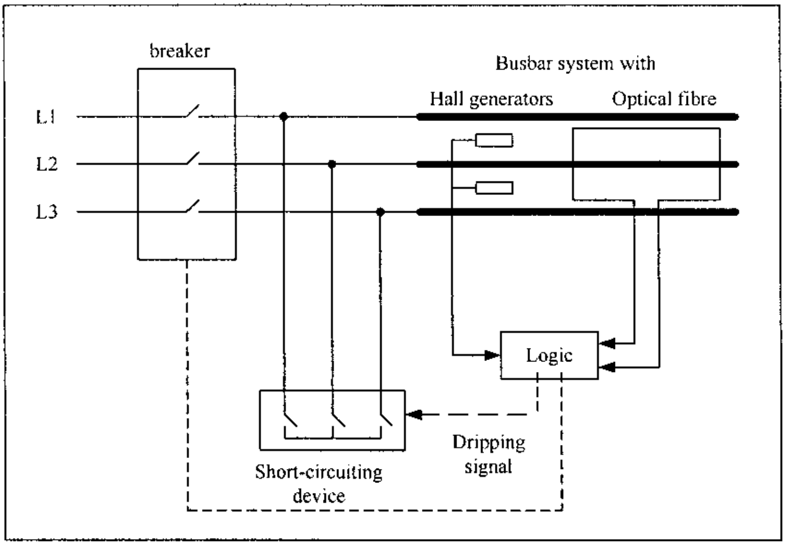

Fig. 7: Principle scheme of the arc protection system

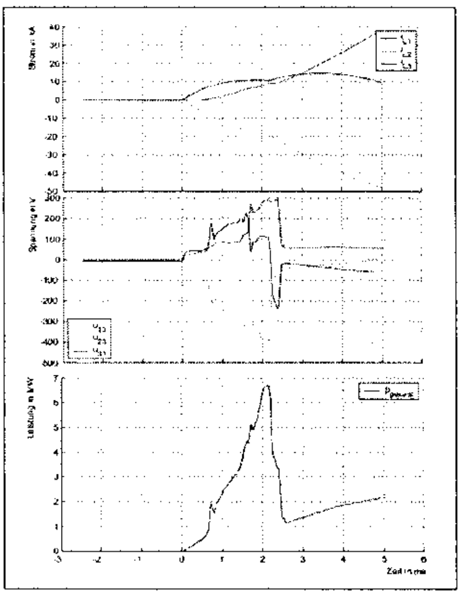

Fig. 8: Oscillogramme of an arcing fault test using the protection system

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